Magnetic Field Characterization, Re-tuning and First Operation of the NIST Undulator on the Duke 1 GeV Storage Ring

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Originally built for an IR FEL project at the National Institute of Standards and Technology, the NIST undulator was acquired by Duke for use as a soft x-ray source on the 1 GeV storage ring. The Brobeck Division of Maxwell Laboratories constructed this 3.64 m long hybrid-design undulator. Initial Hall probe measurements on the magnetic field distribution of the undulator revealed field errors of more than 0.80% RMS. Initial phase errors for the device were more than 11 degrees. A series of in-situ and off-line measurements and modifications were employed to re-tune the magnetic field structure. Initial goals for the device called for the production of strong spectral characteristics through the 5th harmonic. Although rms field errors remained rather high (~0.75%), phase errors were reduced to less than 5 degrees. A diagnostic beamline including a transmission grating spectrometer and a scanning wire beam profile monitor was constructed to characterize the spatial and spectral characteristics of the radiation. We report on this effort and the resulting first operation of this undulator source.

Introduction

The Duke University storage ring has been designed for use as a third generation driver for FEL and undulator insertion devices. At a storage ring energy of 1 GeV, the NIST undulator can provide a high brightness source of quasi-coherent first harmonic radiation in the wavelength range between 37 - 45Å. Moreover, with storage ring operation at 500MeV the undulator output is in the 130Å range which is useful for EUV lithography studies.

The NIST undulator is a 3.64-m hybrid design with 130 2.8-cm period lengths. Each half-period magnet assembly consists of 2 SmCo permanent magnets and one vanadium permendur pole piece. The undulator can be operated in either half-length or full-length configurations with an adjustable taper. The initial inspection of the Duke/NIST undulator revealed numerous poles that were dislodged from their support base. It quickly became apparent that the undulator arrived at Duke with serious magnetic field errors. This confimed the previous attempts to characterize the undulator while at CEBAF using the pulse wire technique (1). It was decided that the undulator would be re-tuned to take advantage of advances in metrology and field-correction technologies (2). Once the magnetic field distribution was known, one could re-tune the undulator to maximize the spectral output of the device.

Magnetic Field Characterization

The typical method used to characterize the field distribution of an undulator is to scan the device at the desired operational gap with a precision magnetometer. From the B_y versus z data along the electron beam axis of the undulator one can compute the radiation spectrum, the electron trajectory and the displacement of the electron beam. To that end, a very low friction cart was constructed designed to ride along the surface of the granite rails, which rested on three point supports on the undulator C-frame. The cart supported two standard linear and one rotation optical stages, which allowed a GMW Group 3 low profile Hall probe to be positioned in space and orientation within the gap of the undulator. The system was designed for the highest accuracy and reproducibility possible. At a 5 kHz sampling rate, the localized Hall probe fluctuations in magnetic fields were reduced to ±0.50 G. Overall, probe uncertainty accounts for 0.08% of the rms field error and a <15 G-cm variation in the field integral. An Accu-Rite glass linear encoder tracked the linear position of the cart along the rail. The entire system was computer controlled and capable of producing high resolution scan data of the undulator in the form of B_y(Gauss) vs. z(cm) with a accuracy of +/- 0.5 Gauss and +/- ~100μm along the undulator axis.

The half pole assemblies from one half of the undulator were removed from their support girder and characterized and corrected off-line. With measured pole height variations of as much as .009", each base was trimmed and the pole tilts were also corrected to within .0005" end to end. Using a magnetic steel (10-08) yoke constructed to approximate the undulator field at a gap of 20 mm, the magnetic field strength for each individual half-pole assembly was measured. In addition, the ratio of air gap field to the full saturation field was measured. This data allowed us to do some re-sorting of the original magnetic distribution for the exit half of the undulator using a simulated annealing algorithm (3). Magnets that were heavy outliers were placed at the exit end of the undulator where their adverse impact could be more easily compensated for by the end corrector.

Following reassembly of the undulator, the magnetic field distributions of both halves of the undulator were mapped by our Hall probe based magnetic measurement system. In order to maximize the potential for success, each half of the undulator was tuned separately. After one was satisfied with the performance of the two potential half undulators, the gaps would be matched to create the full-length device. IDL code titled MA was used for much of the data analysis (4). MA calculated the phase errors, angular kick corrected trajectories, and the single particle spectrum for a given set of magnetic field distribution data and provided a quick way to check the progress of the re-tune efforts.

Initial scans of the untuned device revealed rms errors of approximately 0.79%. In addition, phase errors were rather large as well at more than 11 degrees rms. The real figure of merit for the device is the single particle spectra. Based on the initial scans of the exit half of the device, in the first harmonic we only manage to generate ~83% of the maximum one would expect under perfect conditions. The third harmonic becomes completely washed out and leaving only about 34% of theoretical

maximum. The fifth harmonic is negligible under the initial analysis. The results for the scan of the entrance half of the undulator showed similar results for the first harmonic. The re-sort helped improve harmonic performance generating a third harmonic spectrum of 65% and a fifth harmonic of 51% of theory.

To correct the remaining field errors of the device we employed 4 different methods to transform the Duke/NIST undulator into a useable source of radiation. DC bias fields, pole swapping, pole shimming (5), and application of corrector coils was all used to fix the undulator. It was determined that the base and girder structure had remnant field creating an overall bias curve in the trajectory. To compensate for this DC offset an opposite bias field on-axis was created by wrapping the top half of each undulator half in coil. In addition, pole assemblies were also swapped and shimmed at various places to correct the angular kicks produced by poles that were out of specification.

Phase errors were reduced from approximately 8.5° down to less than 3° for the entrance half and from 11° down to 3° for the exit half. The first integral was reduced from greater than 600 G-m in both cases to less than 325 G-m. Performing more detailed calculations to take into account the real magnetic field distribution and emittance effects, one would expect to achieve 87% and 98% of the maximum brightness in the 1st harmonic for the entrance and exit halves, respectively. In the 3rd harmonic, one would expect 87% and 94% (entrance/exit) of the maximum value. For the full-length configuration one expects to achieve 88% of the maximum in the 1st and 75% in the 3rd harmonic.

First Light Operation

Driven by a series of concerns and constraints regarding utility, personnel safety and funding, a unique front-end and diagnostic beamline for the undulator was constructed. The front end has been designed for maximum throughput of the 1st harmonic around 40Å. This compact system facilitates the extraction of some of the bend-magnet-produced synchrotron and transition radiation from the storage ring. As with any well designed front-end system, it also provides excellent protection to personnel and to the storage ring. The diagnostic beamline consisting of a transmission grating spectrometer and scanning wire beam profile monitor was constructed to measure the spatial and spectral characteristics of the undulator radiation. The transmission grating spectrometer (TGS) consists of a 2000 Å period (5000 lines/mm) free standing gold transmission grating, a Si XUV photodiode, and various combinations of pinholes and slits all mounted in standard crosses. The spectrometer is based on the work of Heiman and Gulikson (6). The TGS with a 50-µm slit in front of the diode has a spectral width of 0.164 Å or a bandwidth ($\Delta\lambda/\lambda$) of 1/244 at 40 Å.
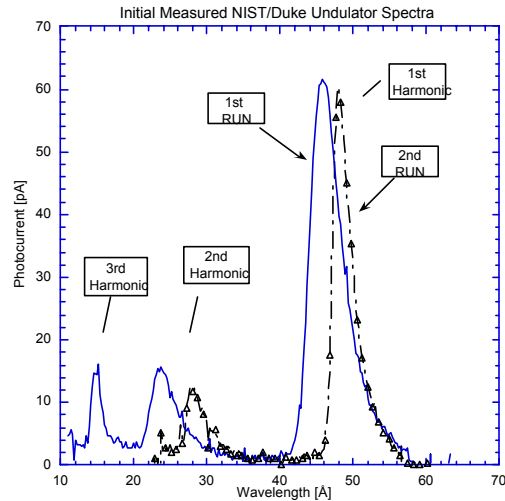
FIGURE 1. First Spectrums from NIST/Duke Undulator

The beamline received its first synchrotron light from the downstream bending magnet in January of 1998 with first light through the undulator occurring in February of that same year. With a storage ring current of 5.6mA and energy of 1 GeV the undulator gap was closed to a nominal setting of 20mm. Figure 1 (1st Run) presents the first spectrum from the undulator. The nominal wavelength was approximately 46Å and the 2nd and 3rd harmonics are clearly visible. The spectrum observed was quite broad due to a lack of beam steering opportunity limited by stable beam time. With the next run the opportunity for limited steering was present which resulted in slightly improved spectral bandwidth (figure 1 – 2nd Run).

The NIST/Duke Undulator is finally operational after an extensive effort to measure and re-tune the magnetic structure. The device has the potential to become a very bright source of EUV and Soft X-ray radiation. The Duke storage ring will be able to fully support high-energy operation in the near future. At that time the radiation output from the undulator can be optimized and measured further.

Acknowledgements

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